Keep it short: Exploring the impacts of configuration choices on the recent economics of solar-plus-battery and wind-plus-battery hybrid energy plants

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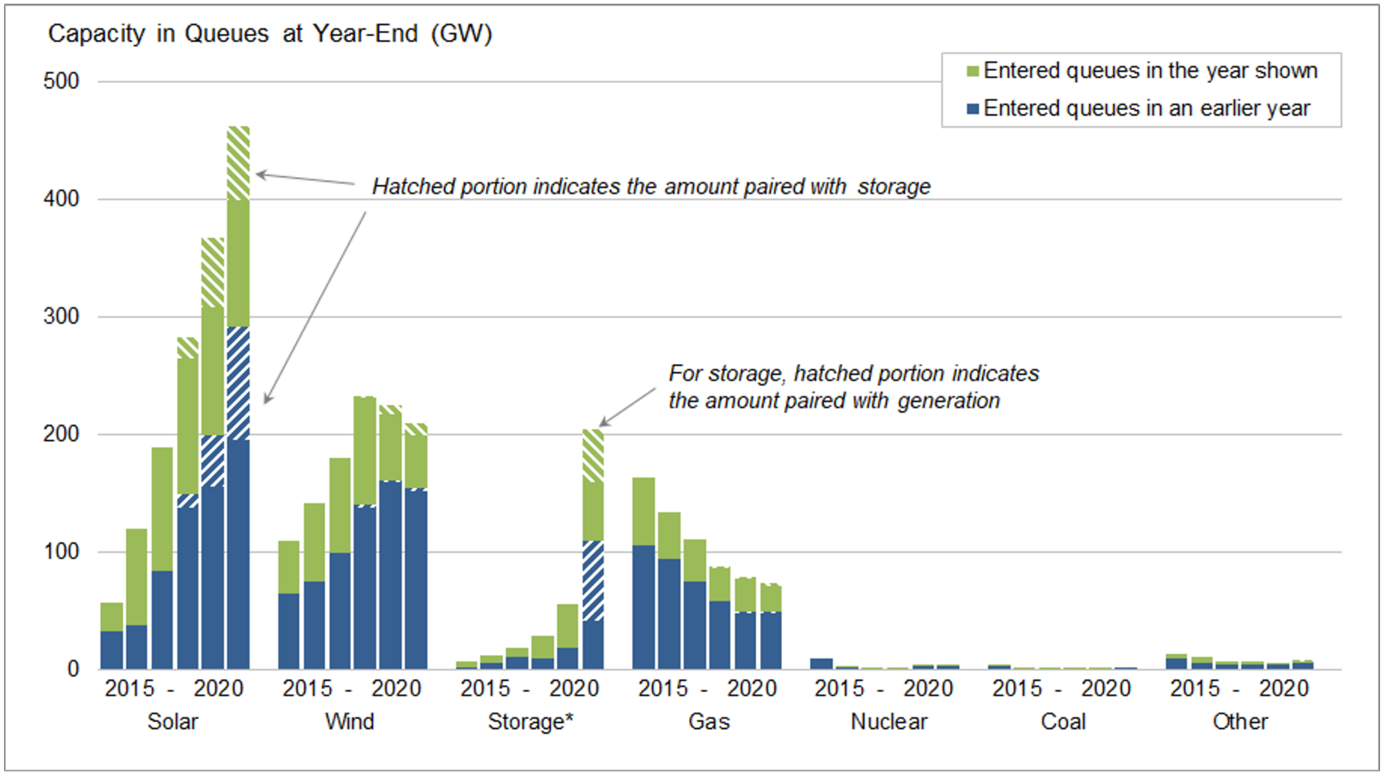
Interconnection queues indicate rapidly growing commercial interest in hybridization



Understanding what hybrid configurations are being deployed is important for system planners responsible for reliability and transmission planning.

*Hybrid storage capacity is estimated using storage:generator ratios from projects that provide separate capacity data. Storage capacity in hybrids was not estimated for years prior to 2020.

Note: Not all of this capacity will be built
Source: Berkeley Lab review of 37 ISO and utility interconnection queues

How do developers make configuration choices? Evaluate a strategy to design hybrids

Design through *hybrid net value* calculation

- Find attractive candidates based on a marginal analysis of market value and cost
  - Value: optimized wholesale revenue under constraints for different **configuration parameters**
  - Costs: based on **configuration parameters** and costs literature
    - **Battery lifetime depends on operational profile**
- Attractive technologies = highest profitability
  - Measured as difference of revenue and cost
  - Construct a **hybrid net value indicator**

Objective: Identify hybrid configuration choices with highest impact on hybrid net value under different plausible scenarios

Alternatives in the literature (not used here)

Design to meet technical requirements

- Define technical specifications (e.g., performance parameters, reliability thresholds, target generation profiles)
- Identify configurations that meet those specifications at least cost

Design in capacity expansion models

- Define hybrids as candidate resource in models
  - Identify design options and cost relationships
  - Define performance capabilities
- Include system-wide reliability constraints
- Find portfolio of resources that maximizes planning objective

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Using hybrid net value to understand the economic attractiveness of hybrid plants

Construction: Subtract the annualized hybrid cost from from the annual market value of a co-located VRE generator and storage plant ***for different configuration parameters***.

Annual market value and costs are normalized using the standalone VRE generation

Consider both choice of scenario and configuration parameters:

- Scenarios are ***exogenous parameters*** that frame the hybrid plant's operation
- Configurations are ***endogenous choices*** made by the developer when designing a hybrid plant

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Wholesale market value

- Hourly dispatch, price taker analysis
- Dispatch to maximize revenue
- Linear degradation penalty

\-

Cost calculation

- Battery pack lifetime

End-of-life battery costs based on fatigue cycling

- Hybrid costs

Generator CAPEX
+ Battery CAPEX
+ Generator OPEX
+ Battery OPEX

= **Hybrid Net Value ($/MWh)**

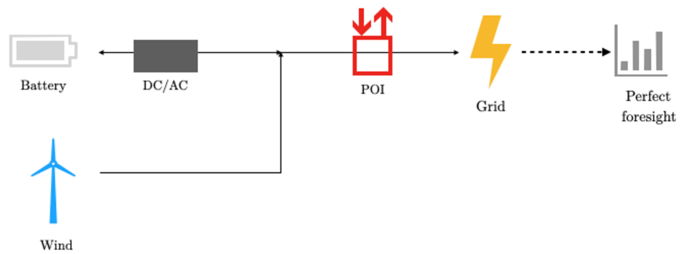
Note: more details on the methodology are provided in Appendix

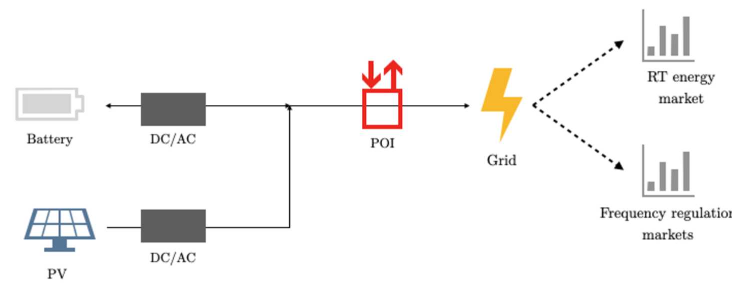
How does hybrid net value change across scenarios and configuration choices?

		Parameter	Range	Effect on coupled value
Scenarios		Incentives	ITC/PTC at 2020 levels; none	Including incentives lowers the cost of the hybrid plant
Scenarios		Dispatch algorithm	Perfect foresight; Day-ahead schedule	Perfect foresight leads to higher revenues through omniscient operation; using day-ahead prices for scheduling is naïve, but implementable
Scenarios		Degradation penalty	$0/MWh; $5/MWh; $25/MWh	Higher penalty reduces cycling, decreasing revenue but limiting degradation
Scenarios		Revenue streams	Energy, capacity; energy, capacity, frequency regulation	Participation in ancillary services market increases opportunity of revenue creation
Configurations	Solar, wind hybrids	Storage Size (%)	25%; 50%; 75%; 100% of generator capacity	More capacity → more revenue (though potentially diminishing returns)
Configurations	Solar, wind hybrids	Storage Duration (hrs)	2; 4; 6; 8 hrs	More duration→ more revenue (though potentially diminishing returns)
Configurations	Solar, wind hybrids	Point of Interconnection (MW)	VRE capacity; VRE + battery capacity	• More interconnection capacity → more revenue • Potentially limited impact of constraint due to storage discharging at different times than renewable profile
Configurations	Solar, wind hybrids	Grid charging	Disallow grid charging; Allow grid charging	• Allowing grid charging increases arbitrage opportunities • Value depends on relationship of prices and renewable profile
Configurations	Solar only	Coupling	AC; DC	DC coupling increases VRE output due to clipped energy, increasing revenue
Configurations	Solar only	Inverter Loading Ratio	1.3; 1.7; 2.1	Higher ILR allows excess energy to be stored, increasing revenue

How does hybrid net value change across scenarios and configuration choices?

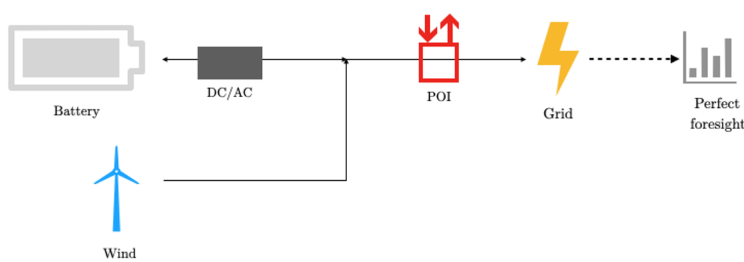
Scenarios

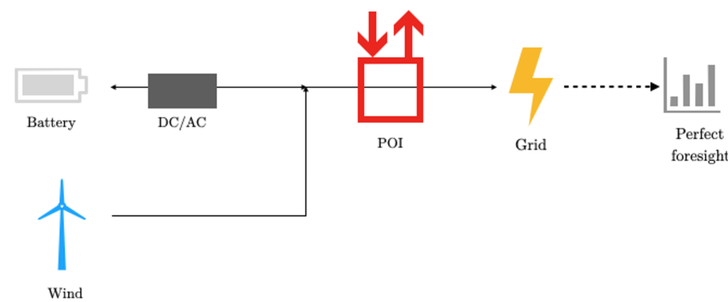




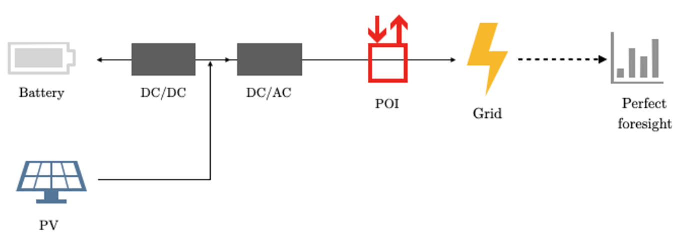
Configurations

Solar, wind hybrids





Solar only

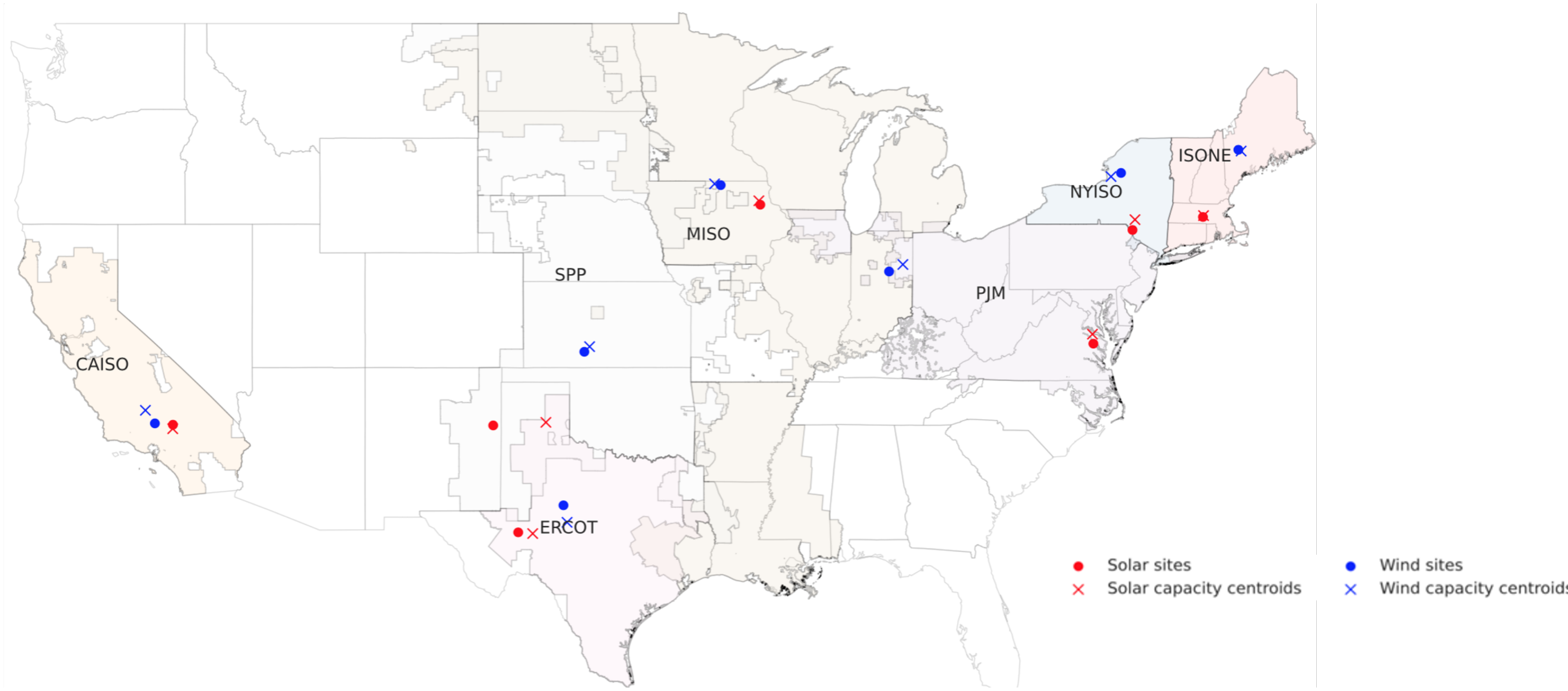


Selection of representative sites in 7 ISOs

Site **one wind** and **one solar hybrid** at a representative location in each of the seven organized wholesale market regions of the U.S.

Sites are selected based on the location of an existing wind or solar plant **nearest to the capacity-weighted centroid** of all currently-installed wind or solar plants.

Candidate sites limited to those with an annual capacity factor within **10% of the average capacity factor** of all existing wind or solar plants in the market (2019).



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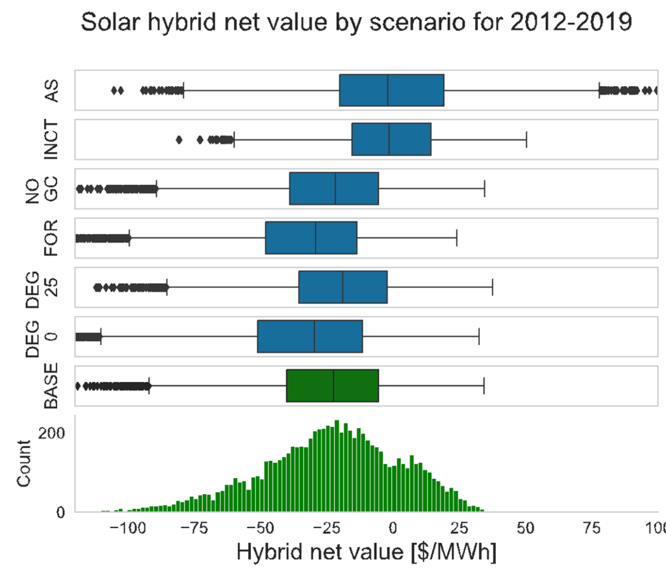
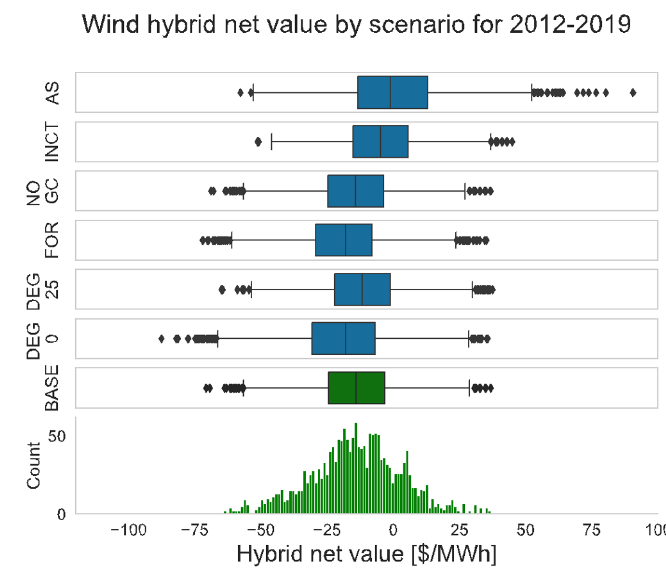
Hybrid attractiveness across plausible scenarios

- Baseline scenario: median net value across all configurations, regions, and years is ***-$22/MWh*** for solar and ***-$14/MWh*** for wind hybrids
  - But even in the Baseline scenario some hybrid configurations can be attractive investments: 20% of the cases have a positive net value in the Baseline scenario

- The scenarios that most impact hybrid net value are the ***Incentives*** and ***Ancillary Services*** scenarios
  - Incentives: $21/MWh for solar and $9/MWh for wind
  - Ancillary Services: $20/MWh for solar and $13/MWh for wind

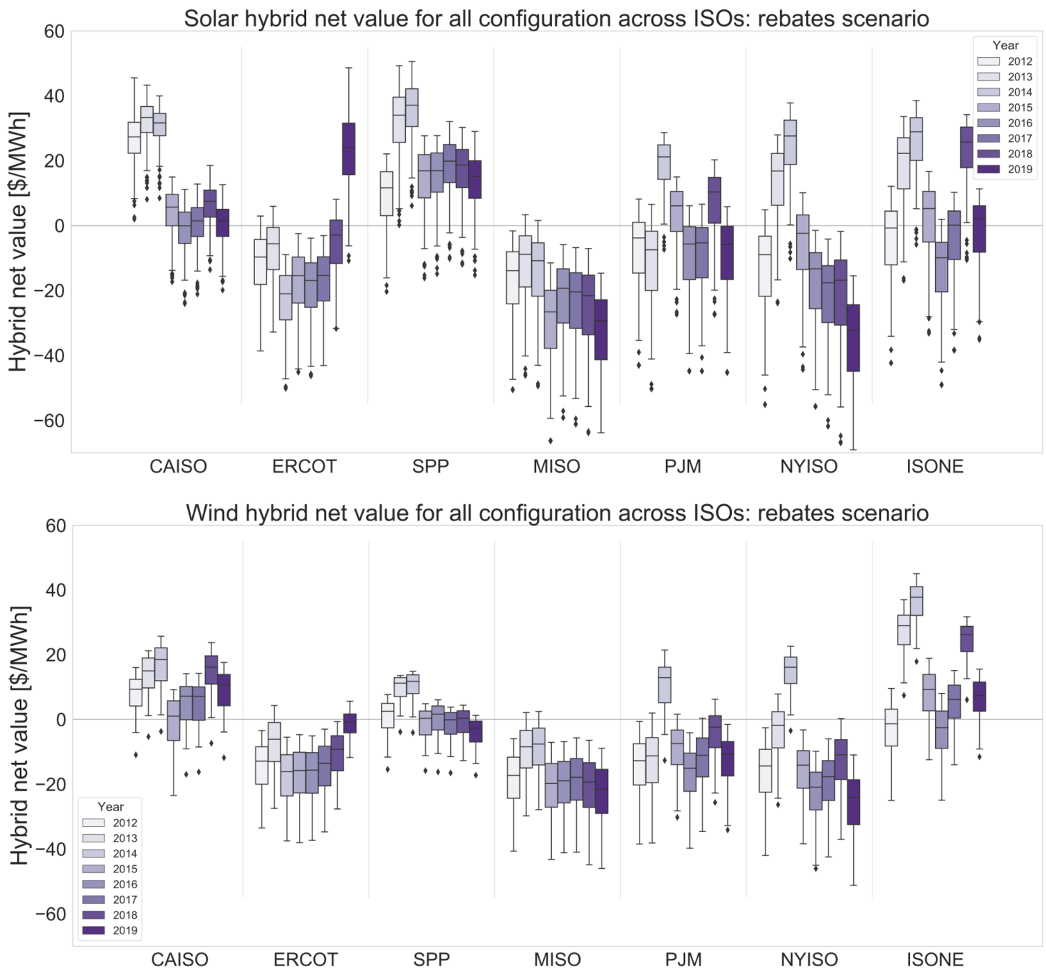




Understanding hybrid net value across modeled years

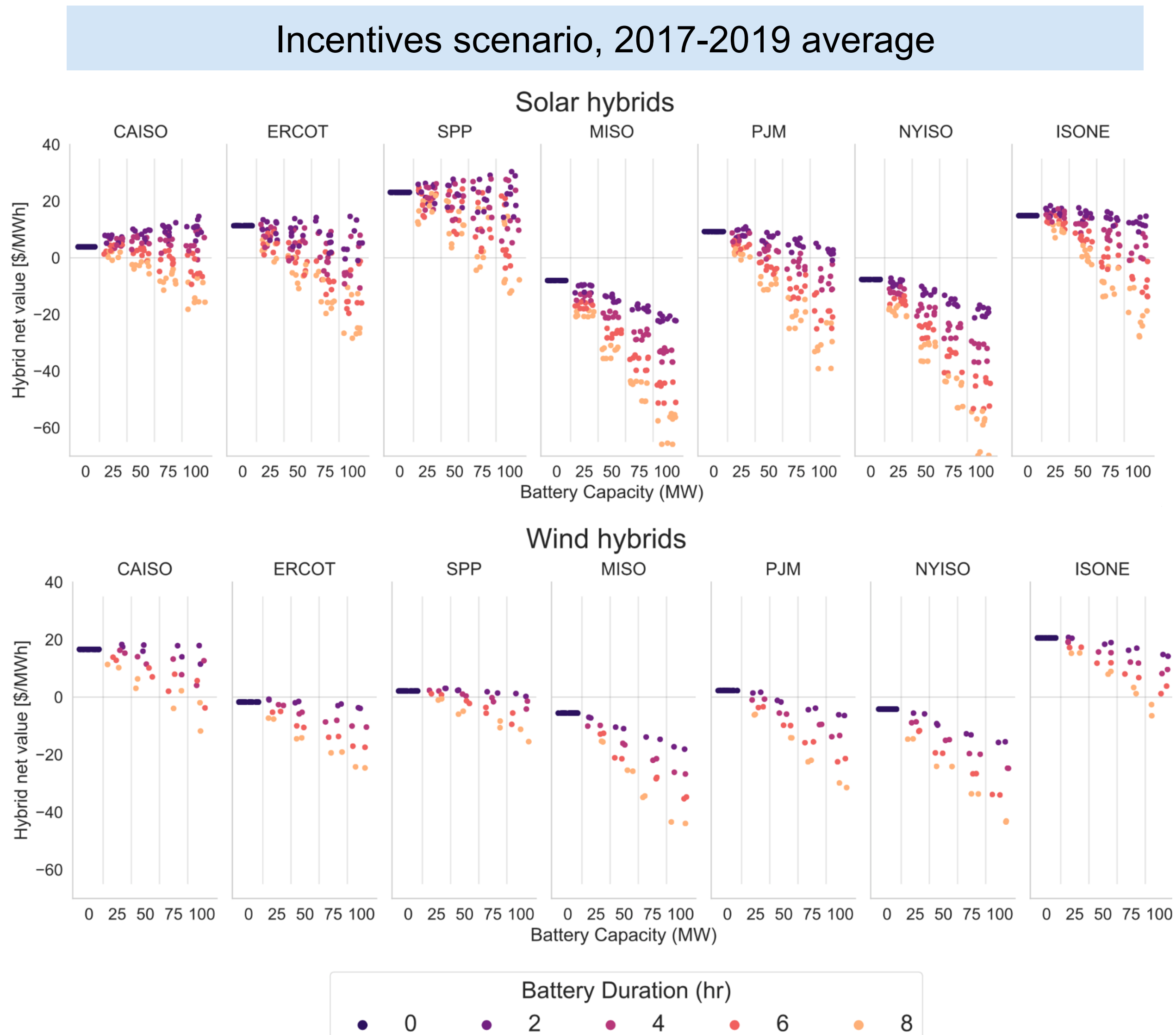
- Wholesale ***market trends*** are important in driving the net value of hybrids
  - Similar year to year variation when comparing solar to wind hybrids
- Market trends do not always similarly impact solar and wind hybrids, however
  - CAISO between 2012-2019 solar shifted the timing of high and low wholesale market prices, leading to a decline in the net value of solar hybrids but not wind hybrids
  - High wholesale market prices in the summer afternoons in ERCOT in 2019 increased the net value of solar hybrids relative to the increase in net value of wind hybrids

Incentives scenario



Storage duration and capacity have the largest impact on the net value of solar and wind hybrids

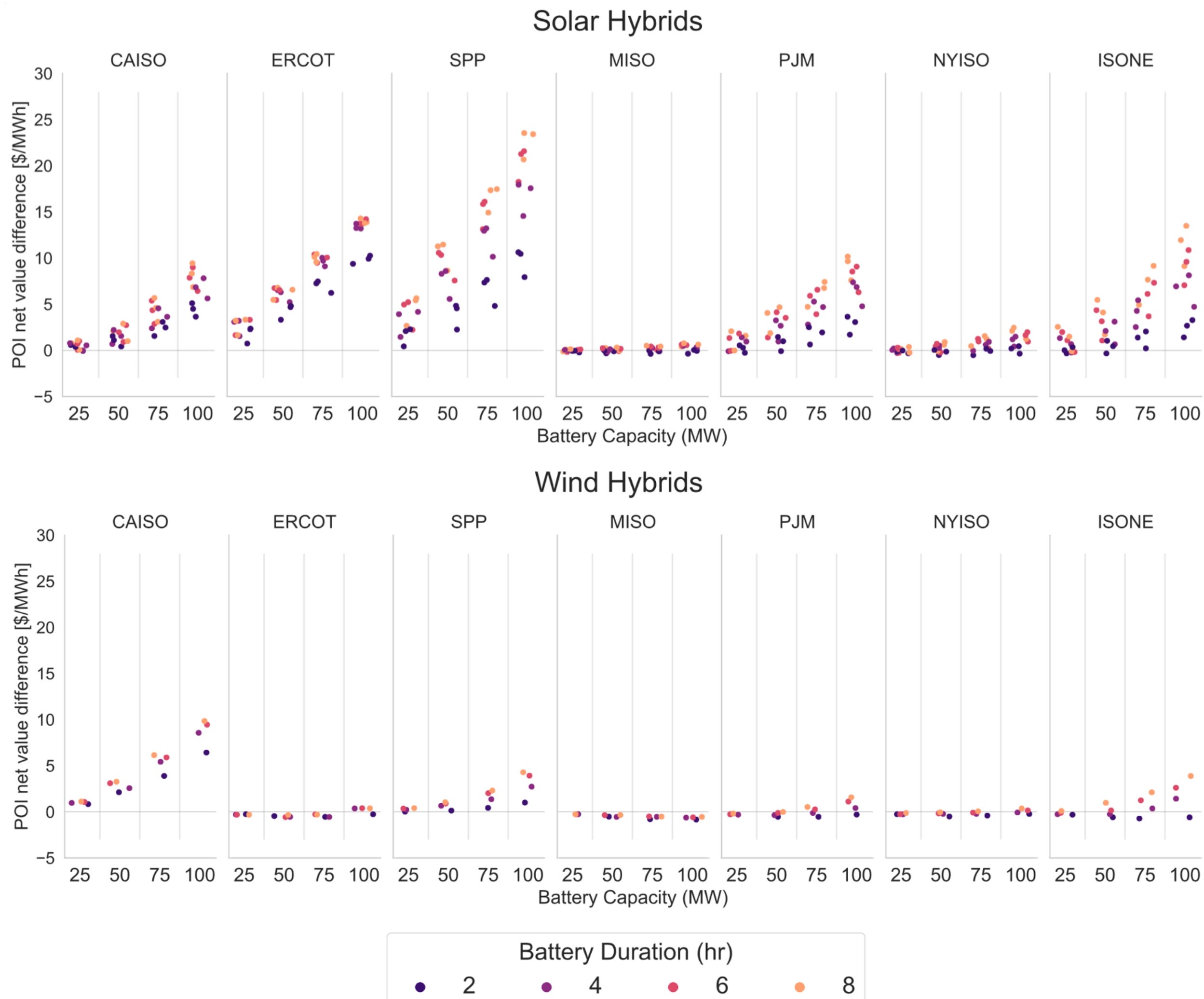
- The configuration parameters that most significantly impact hybrid net value are the storage ***duration*** and storage ***capacity***
  - Hybrid configurations with the highest net value have 2-hour duration storage
  - The costs associated with increasing the duration of storage outweigh the associated increase in market value
  - Yet, in CAISO, SPP, ERCOT solar hybrids with 100 MW storage are most attractive in the Incentives scenario



Net value often increases with sufficient interconnection capacity to discharge generator and storage

- The "POI effect" increases with ***larger storage capacity*** and with longer storage duration
- For ***solar*** hybrids:
  - ERCOT, SPP: Extra POI capacity allows solar to produce at full output at the same time that storage is fully discharging
  - CAISO: Extra POI relatively less important → peak prices have shifted toward the early evening, away from times of peak solar production

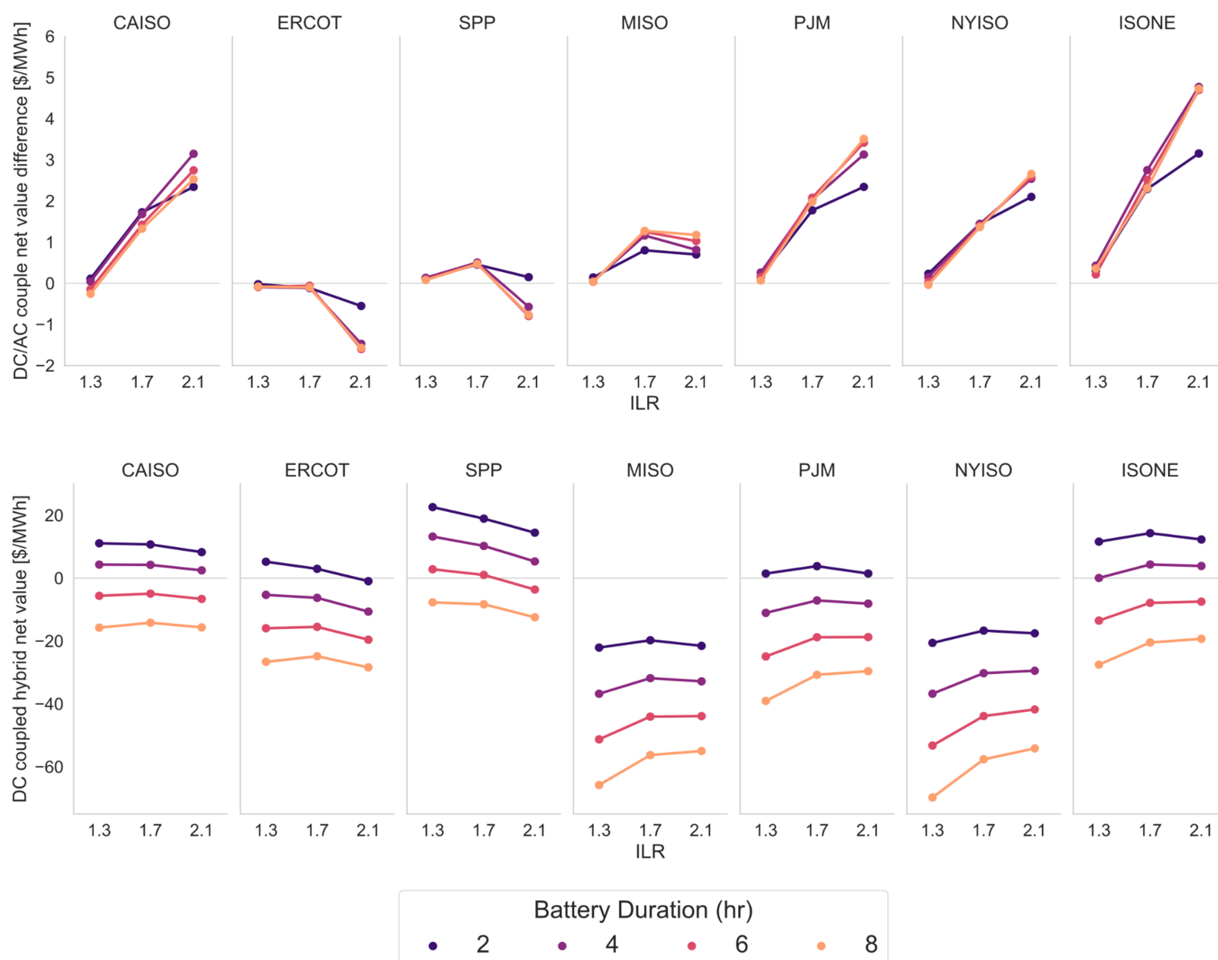
Incentives scenario, 2017-2019 average



Choice between AC and DC coupling and the sizing of the PV panels relative to the inverter are secondary

- AC vs. DC coupled and ILR, apply solely to solar hybrids and impact the net value by about ***$5/MWh or less***
  - DC coupled configurations often have a higher net value, which increases with ILR, than otherwise similar AC coupled configurations (exception of ERCOT and SPP)
  - For DC coupled solar hybrids with 2-hour duration storage, the highest net value ILR is 1.3 in CASIO, ERCOT, SPP and ISO-NE or 1.7 in MISO, PJM, and NYISO

Solar hybrids, Incentives scenario, 2017-2019 average



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Economic framework helps to understand commercial hybrid development activity

Comparison to (1) characteristics of hybrid projects deployed across the US, (2) hybrid plants that have secured offtake and (3) active hybrid projects in interconnection queues

Agrees

- Solar hybrids are more common than wind hybrids
- Solar and wind hybrids are most common in CAISO, with substantial commercial activity in ERCOT and SPP
- Storage durations are typically between 1-4 hours
- Storage to generator capacity ratios are larger for solar than wind hybrids and are largest in CAISO

Disagrees

- Hybrids in the CAISO interconnection queue have a point of interconnection capacity similar to the renewable generator capacity

Not enough data

- Limited data on preference between AC and DC-coupled projects
- DC-coupled projects employ ILRs at or above the range of ILRs typical for standalone PV

Results in terms of hybrid net value, choice of storage duration, and the size of storage capacity help understand commercial hybrid development activity

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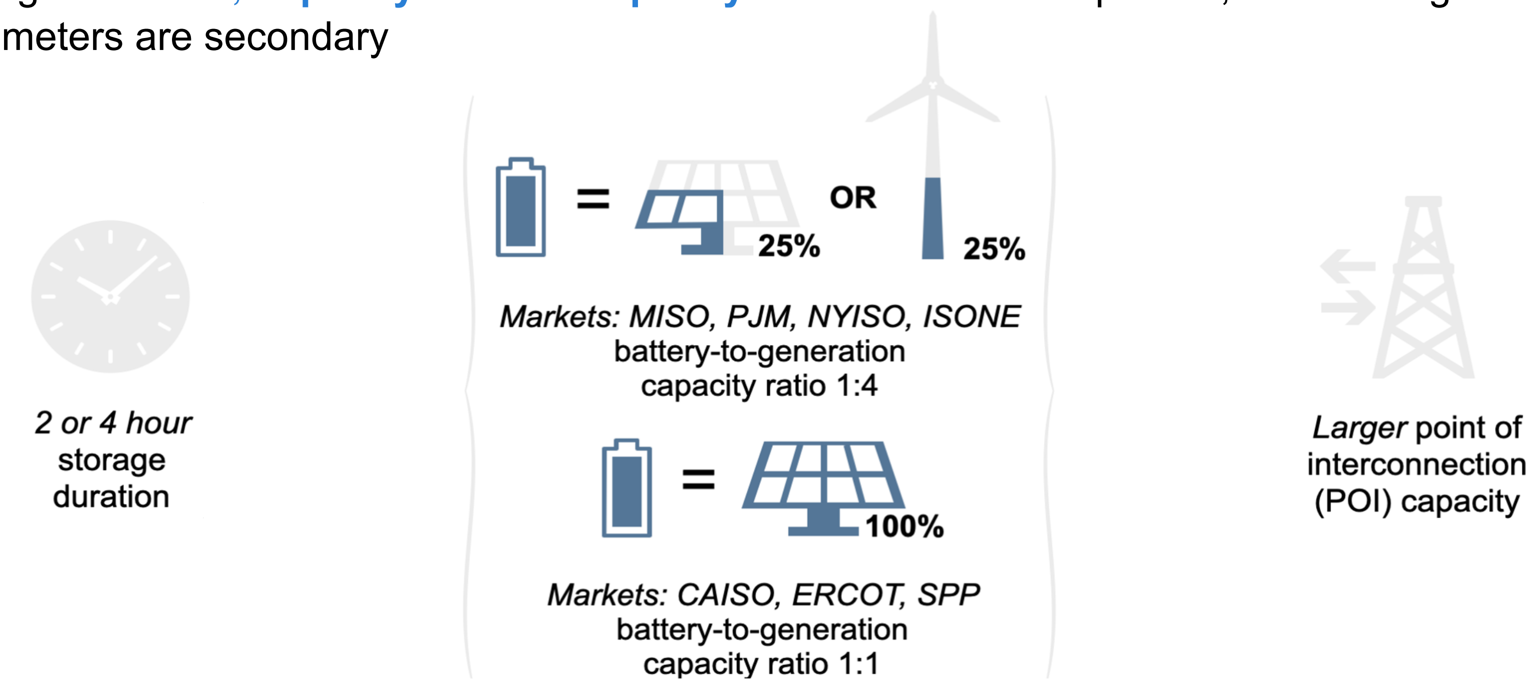
Conclusions

Wholesale **market revenues**, refined **battery cycling dynamics** and bottom-up **costs calculations** can be used together to understand the relative attractiveness of resource options

Scenarios with **incentives** and revenues from **ancillary services provision** lead to the biggest increase in hybrid net value

Storage **duration**, **capacity** and **POI capacity** effects are most important, other configuration parameters are secondary



Results **corroborate commercial trends**, providing **market-specific insights** into how these may change under different scenarios

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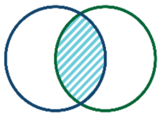
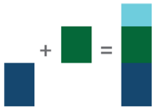
Appendix

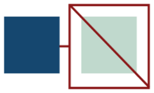
Prior paper outlined the pros and cons of hybridization



+ **Cost Synergies**
- Currently qualify for more financial incentives.
- Shared permitting, siting, equipment, interconnection, transmission, and transaction costs.



+ **Market Value Synergies**
- Policy driven market design rules may value hybrids more than standalone batteries.
- Batteries can capture otherwise "clipped" energy.
- Batteries can reduce wear and tear from thermal generator cycling.



\- **Operational and Siting Constraints**
- Reduced operational flexibility.
- Potentially sub-optimal siting away from congested areas.

+/- **Regulatory Uncertainty**
- Market rules for standalone and hybrid batteries continue to evolve.
- Uncertainty related to the future availability of financial incentives (e.g., federal ITC).

Read more:

The Electricity Journal
Volume 33, Issue 5, June 2020, 106739

Motivations and options for deploying hybrid generator-plus-battery projects within the bulk power system

https://doi.org/10.1016/j.tej.2020.106739

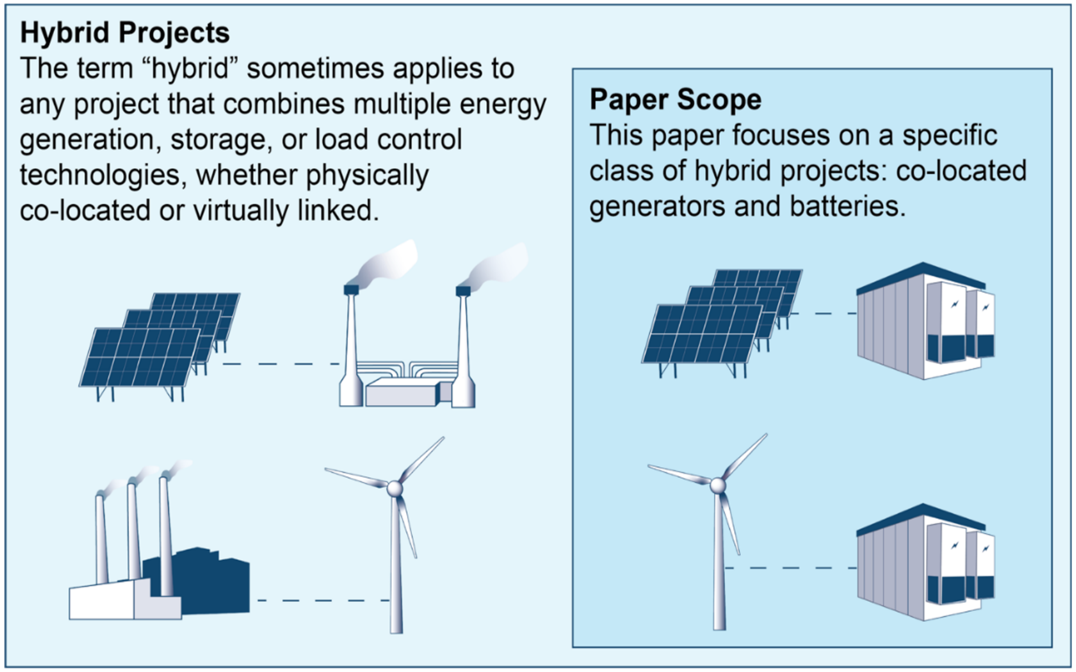
Economic arguments for hybridization (vs. standalone plants) focus on opportunities to reduce project costs and enhance market value

Not all of these drivers reflect true system-level economic advantages, e.g., the federal ITC and some market design rules that may inefficiently favor hybridization over standalone plants

Possible disadvantages of hybridization include operational and siting constraints

If reduced operational flexibility is, in part, impacted by suboptimal market design then this too does not reflect true system-level economic outcomes

We only consider renewable-plus-battery hybrids due to current commercial interest in these applications



Out of scope examples:

(1) Multiple generation types (e.g. PV + wind)

(2) Alternative storage types (e.g. wind + pumped storage, concentrating solar power)

(3) Virtual hybrids with distributed technologies

(4) Full hybrids with operational synergies

Overview of modeling framework

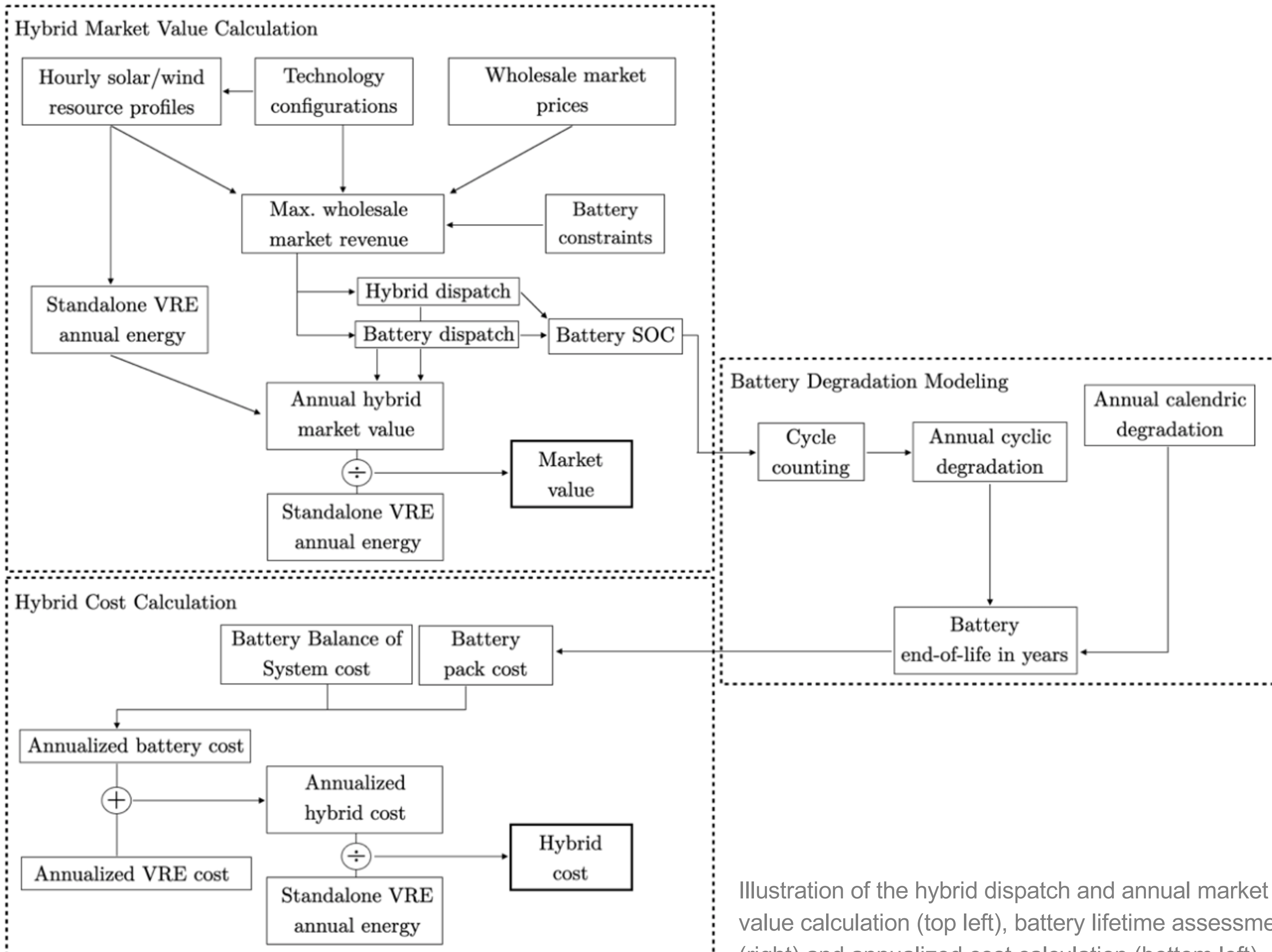
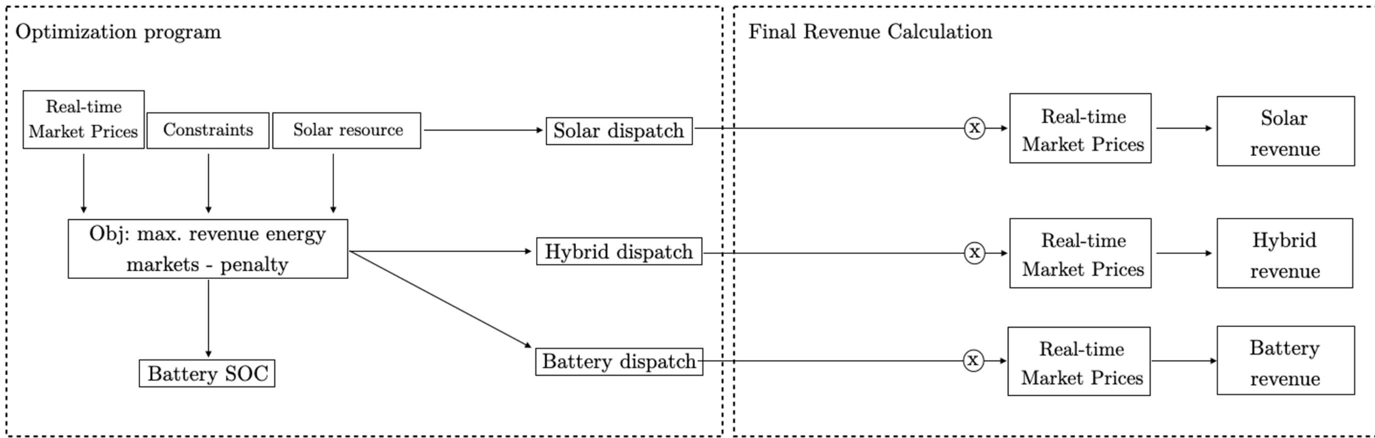
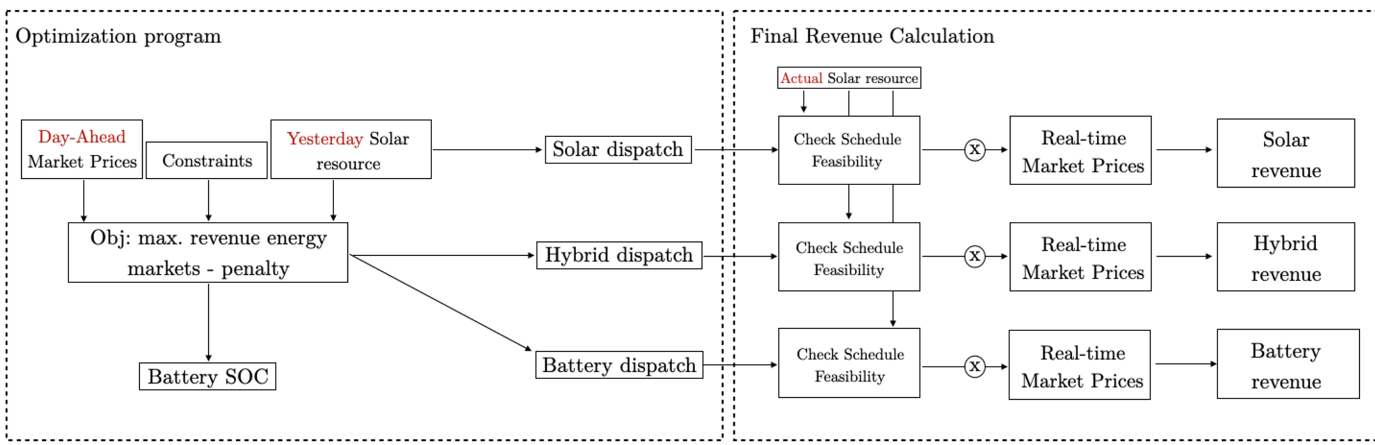


Illustration of the hybrid dispatch and annual market value calculation (top left), battery lifetime assessment (right) and annualized cost calculation (bottom left).

Comparison perfect forecast to Day-ahead schedule model



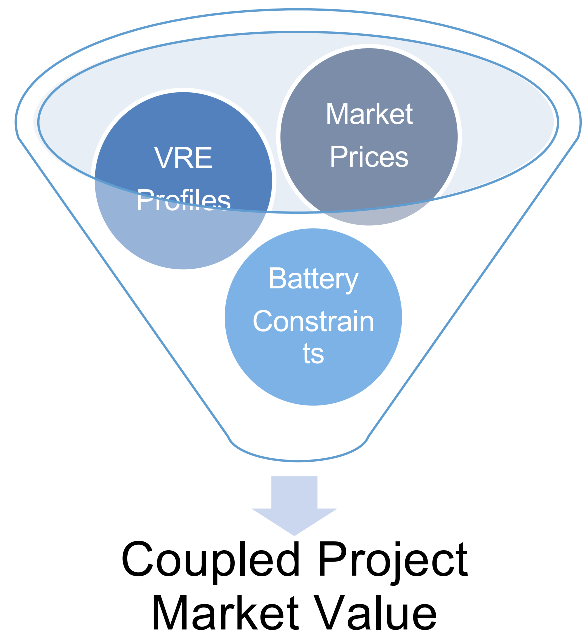


Calculation of value: price taker market optimization

- **Optimization**
  - Price taker analysis means resources do not impact marginal price
  - **Optimistic:** maximizes real-time energy market revenue with perfect foresight
  - **Pessimistic:** develop optimal schedule with day-ahead prices □ realized revenue calculated from real-time energy market

- **Key Inputs**
  - **LMP prices** at nodes with utility-scale solar, wind, and high volatility
  - Average annual capacity price allocated to production in **top 100 net load hours**
  - Regulation prices at ISO zonal level *[used only as a sensitivity analysis]*
  - PV profiles modeled from **weather data**, standard design assumptions
  - Wind profiles modeled from **ERA5** weather data, standard wind power curve

- **Key Outputs**
  - Energy, capacity, regulation revenues (**levelized using generation from VRE**)



Base case optimization algorithm

Objective function:

$$Max \sum_1^{8760}[(P_{rt} + P_c/N * NL_m) * G_i] - [D_p * (B_d + B_c)]$$

Subject to:

Beginning state of charge: $S_0 = 0$

State of charge range: $0 \le S_k \le S_{max}$

Power in rate: $0 \le B_C(k) \le B_{max}$

Power out rate: $0 \le B_d(k) \le B_{max}$

Non-simultaneity rule: $B_d(k) + B_C(k) \le B_{max}$

Battery state of charge: $S_{k+1} = S_k + \left[\eta B_C(k) - \frac{B_d(k)}{\eta}\right]$

AC-grid limits: $-I_g B_{max} \le G_i(k) \le POI$

AC-grid balance: $G_i(k) = W(k) + B_d(k) - B_C(k)$

Curtailment allowance: $W(k) \le G_{VRE}(k)$

Where the decision variables are,
G_i = hourly net electricity profile of coupled or storage system (MWh)[10]
B_d = battery discharging (MWh)
B_c = battery charging (MWh)
S_k = battery state of charge at time step k (MWh)
W_k = power generated from renewable resource at time step k

Where the input parameters are,
P_{rt} = hourly real time electricity ($/MWh)
P_c = capacity price ($/MW)
NL_m = hourly indicator (0 or 1) for top N net-load hour for given market
N = number of top net-load hours, set to 100 in this analysis (h)
D_p = degradation penalty ($/MWh)
B_{max} = battery max power capacity (MW)
S_{max} = total energy capacity of battery (MWh)
η = battery one-way efficiency (%)
I_g = binary indicator to allow grid charging (1 allows grid charging, 0 restricts charging to available VRE)
POI = point of interconnection limit
G_{VRE} = standalone VRE generation profile

Ancillary service optimization algorithm

Expanded Optimization model with ancillary service value

Terms which are bolded in blue below represent the additional terms which are added to the original optimization formulation to take into account regulation reserve values.

Objective function:

$$Max\sum_{1}^{8760}[(P_{rt} + P_c * NL_m) * (G_i + \boldsymbol{\gamma R_i})] + [\boldsymbol{R_i * P_{as}}] - [D_p * (B_d + B_c + \boldsymbol{\gamma R_i})] \quad \text{(Eq. 1)}$$

Subject to:

Beginning state of charge: $S_0 = 0$ (Eq. 2)

State of charge range: $0 \le S_k \le S_{max}$ (Eq. 3)

Power in rate: $0 \le B_C(k) \le B_{max}$ (Eq. 4)

Power out rate: $0 \le B_d(k) \le B_{max}$ (Eq. 5)

Non-simultaneity rule: $B_d(k) + B_C(k) \le B_{max}$ (Eq. 6)

Battery state of charge: $S_{k+1} = S_k + \left[\eta B_C(k) - \frac{B_d(k)}{\eta}\right]$ (Eq. 7)

AC-grid limits: $-I_g B_{max} \le G_i(k) \le POI$ (Eq. 8)

AC-grid balance: $G_i(k) = W(k) + B_d(k) - B_C(k)$ (Eq. 9)

Regulation constraint: $\boldsymbol{R_i + B_C(k) \le B_{max}}$ **(Eq. 10)**

Regulation constraint: $\boldsymbol{R_i + B_d(k) \le B_{max}}$ **(Eq. 11)**

Regulation AC constraint: $\boldsymbol{R_i + |G_i(k)| \le}$ **POI** **(Eq. 12)**

Where,
P_{rt} = hourly real time electricity ($/MWh)
P_c = capacity price ($/MW)
NL_m = hourly indicator (i.e. 0 or 1) for top 100 net load hour for given market
G_i = hourly net electricity profile of hybrid or storage system (MWh)[12]
γ = regulation energy served fraction (%)
R_i = hourly regulation reserve profile of hybrid or storage system (MWh)
P_{as} = hourly regulation reserve price ($/MWh)
D_p = degradation penalty ($/MWh)
B_d = battery discharging (MWh)
B_c = battery charging (MWh)
B_{max} = battery max power capacity (MW)
S_k = battery state of charge at time step k (MWh)
S_{max} = total energy capacity of battery (MWh)
η = battery one-way efficiency (%)
I_g = binary indicator to allow grid charging (i.e. 1 allows grid charging, 0 restricts charging to available VRE)
POI = Point of interconnection limit
W_k = power generated from renewable resource at time step k

DC-coupled optimization algorithm

Expanded Optimization model for DC-coupled Hybrids

Terms which are bolded in blue below represent the additional/changed terms which are added to the original optimization formulation to take into account DC-coupling.

Objective function:

$$Max \sum_{1}^{8760}[(P_{rt} + P_c * NL_m) * G_{ac}] - [D_p * (B_d + B_c)] \quad \text{(Eq. 13)}$$

Subject to:

Beginning state of charge: $S_0 = 0$ (Eq. 14)

State of charge range: $0 \le S_k \le S_{max}$ (Eq. 15)

Power in rate: $0 \le B_C(k) \le \frac{B_{max}}{\propto}$ (Eq. 16)

Power out rate: $0 \le B_d(k) \le \frac{B_{max}}{\propto}$ (Eq. 17)

Non-simultaneity rule: $B_d(k) + B_C(k) \le \frac{B_{max}}{\propto}$ (Eq. 18)

Battery state of charge: $S_{k+1} = S_k + \left[\mu B_C(k) - \frac{B_d(k)}{\mu}\right]$ (Eq. 19)

AC-grid limits: $-I_g B_{max} \le G_{ac}(k) \le POI$ (Eq. 20)

Inverter-out: $\boldsymbol{G_{out-ac}(k) = G_{out-dc}(k) * \propto}$ **(Eq. 21)**

Inverter-in: $\boldsymbol{G_{in-ac}(k) = G_{in-dc}(k) * \propto}$ **(Eq. 22)**

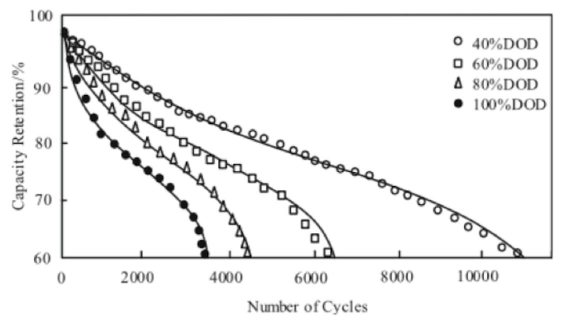
DC-grid balance: $\boldsymbol{G_{in-dc}(k) = G_{out-dc}(k) + B_C(k) - W(k) - B_d(k)}$ **(Eq. 23)**

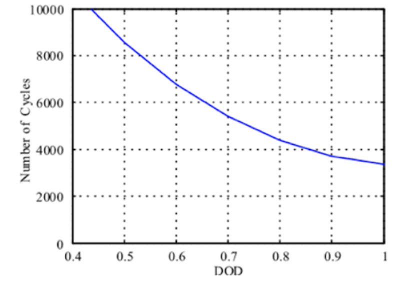
AC-grid balance: $\boldsymbol{G_{ac}(k) = G_{out-ac}(k) - G_{in-ac}(k)}$ **(Eq. 24)**

Where,
P_{rt} = hourly real time electricity ($/MWh)
P_c = capacity price ($/MW)
NL_m = hourly indicator (i.e. 0 or 1) for top 100 net load hour for given market
G_{ac} = hourly AC net electricity profile of DC-coupled hybrid system (MWh)
D_p = degradation penalty ($/MWh)
B_d = battery discharging (MWh)
B_c = battery charging (MWh)
B_{max} = battery max power capacity (MW)
α = inverter efficiency (%)
S_k = battery state of charge at time step k (MWh)
S_{max} = total energy capacity of battery (MWh)
μ = battery efficiency without inverter losses (%)
I_g = binary indicator to allow grid charging (i.e. 1 allows grid charging, 0 restricts charging to available VRE)
POI = Point of interconnection limit
G_{out-ac} = Energy out from the AC inverter (MWh)
G_{out-dc} = Energy out from the battery and/or PV system (MWh)
G_{in-ac} = Energy in from the AC inverter, that is the grid (MWh)
G_{in-dc} = Energy into the battery from the AC inverter and/or PV system (MWh)
W_k = DC power generated from solar resource at time step k

Degradation calculation impact on costs (1)

2018, Gangui Yan et al, *"A cost accounting method of the Li-ion battery energy storage system for frequency regulation considering the effect of life degradation"*



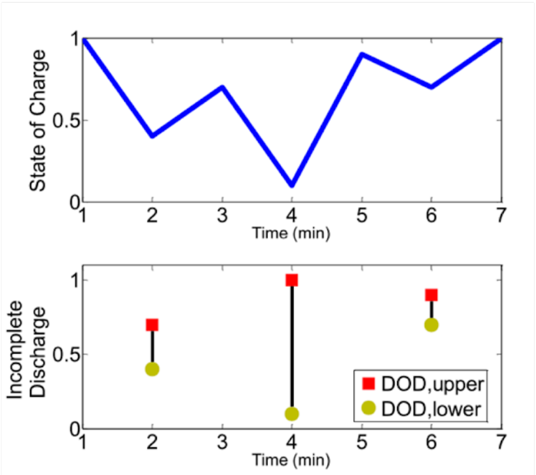


$$C_{DODi} = 28270e^{-2.401DOD_i} + 2.214e^{5.901DOD_i}$$

Pérdida capacidad por ciclo [%]

$$L_{DODij} = n_{DOD}\left(\frac{1}{C_{DODi}} - \frac{1}{C_{DODj}}\right)$$

2018, Niu et al. *2015*, Ke et al. *2018*, Xiao et al.



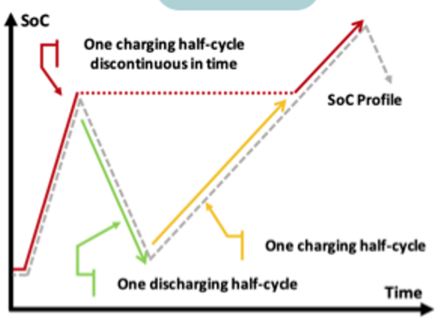
Degradation calculation impact on costs (2)

Annual cycling capacity loss[%]

SOC timeseries

RCA: 3-points

cycles, depth



$$L_{cycling}^{annual} = \sum_{k=1}^{K} L_{DODij}$$

2017, Shi et al, **2018**, Yan et al.

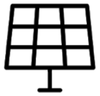
Annual calendar loss [%]

$$L_{calendar}^{annual} = \frac{1}{T}$$

2018, Yan et al. ***2017***, Hesse et al.

$$L_{total}^{annual} = L_{cycling}^{annual} + L_{calendar}^{annual} \longrightarrow EOL[years] = \frac{1}{L_{total}^{annual}}$$

Degradation calculation impact on costs (3)

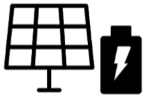


$$LCOE_s = \frac{\text{Annual cost}_s}{\text{Annual energy}_s} + OM_{sv}$$

$$\text{Annual cost}_b = (C_b^{pack} + C_b^{bos} + OM_{bf})C_b$$

$$LCOE_b = \frac{\text{Annual cost}_b}{\text{Annual energy}_s} + OM_{bv}$$

EOL [years]



$$LCOE_h = \frac{(1 - R_{A/D})(\text{Annual cost}_b + \text{Annual cost}_s)}{\text{Annual energy}_s} + OM_{bv} + OM_{sv}$$

Degradation calculation impact on costs (4)

Battery cost modeling

BOS lifetime affects the BOS LCOE (30 years)

Capital cost	Value	Units
storage capital cost power bos	85	$/kW
storage capital cost energy bos	198	$/kWh

Years to EOL affect the pack LCOE (calculated)

Capital cost	Value	Units
storage capital cost power pack	0	$/kW
storage capital cost energy pack	165	$/kWh

2020 - Li-ion LFP

		10 MW					100 MW				
		2h	4h	6h	8h	10h	2h	4h	6h	8h	10h
Storage system	Storage Block $/kWh pack price	176	174	172	171	170	168	165	164	163	162
	Storage Balance of System $/kWh	43	40	39	39	38	41	38	37	37	36
ESS	Power Equipment $/kW	73	73	73	73	73	[illegible]	63	63	63	63
	Controls & Communication $/kW	8	8	8	8	8	[illegible]	2	[illegible]	2	2
	Systems Integration $/kWh	52	47	45	44	43	[illegible]	44	42	42	41
	Engineering, Procurement, and Construction $/kWh	62	56	54	53	52	[illegible]	53	51	50	49
	Project Development $/kWh	75	67	65	63	62	[illegible]	63	61	60	59
	Grid Integration $/kW	25	25	25	25	25	20	20	20	20	20
Energy & capacity Cost	$/kW	106	106	106	106	106	85	**85**	85	85	85
	$/kWh	408	384	375	370	365	385	**363**	[illegible]	352	347
Total ESS Installed Cost	$/kW	$ 922.00	$ 1,642.00	$ 2,356.00	$ 3,066.00	$ 3,756.00	$ 854.00	$ 1,541.00	[illegible]	$ 2,894.00	$ 3,565.00
	$/kWh	$ 461.00	$ 410.50	$ 392.67	$ 383.25	$ 375.60	$ 427.50	$ 384.25	[illegible]	$ 362.63	$ 355.50
Operation Costs	Fixed O&M $/kW-yr	2.24	4.03	5.80	7.56	9.31	2.08	3.79	5.47	7.15	8.82
	Variable O&M $/MWh			0.5125					0.5125		
	System RTE Losses $/kWh			0.005					0.005		
Performance metrics	Round Trip Efficiency %					86%					
	Response Time sec					1-4					
	Cycle Life # cycles					2,000					
	Calendar Life years					10					
	Duration Corresponding to Cycle Life years					5.77					

2021, PNNL Storage Technology Database